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The interaction of the downslope winds and fog formation over the Zagreb area

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ABSTRACT

This study investigates fog development over the greater Zagreb area; a long-lasting fog event that took place from 6 to 8 November 2013. According to climatological data, haze and fog occur frequently over the Zagreb airport area and cause severe low visibility that can last for several days. The Zagreb airport is located on a flat terrain south of Zagreb near the Sava River. North of Zagreb, Medvednica Mountain rises up to 1000 m above sea level over a relatively short distance of approximately 10 km, with a very well-defined downslope forest area.

The here selected case was analyzed by means of available meteorological and air quality measurements and numerical simulations performed by the WRF-ARW high-resolution numerical model. The model was able to reproduce this fog event with some differences among the various model setups. The influence of the Sava River was also estimated by the additional calculation of backward/forward trajectories.

The results revealed the roles of (i) downslope wind, which usually occurred over the city when the net radiation over the Medvednica slopes became negative, and (ii) the urban Zagreb area. Maximum wind speeds occurred at a height of approximately 300 m above ground level, which was slightly above the temperature inversion at the intersection between the slopes and the city. When the downslope flow experienced a hydraulic jump at the lower part of the slope, the downslope flow did not progress significantly over the Sava River or to the south. Then the fog is shallow and dense, staying away from the city. Under certain conditions, the extent of the katabatic flow can reach the airport area. Then the effect of the downslope flow was not apparent in the surface layer over the airport; however it existed above the thermal inversion layer, which contributed to fog persistence.

The possible influences of the Sava River and urban heat island (UHI) on fog were relatively small. The largest river effect is most likely at stations that are located northeast of the river. The UHI can contribute to the formation of katabatic winds under clear-sky conditions in the afternoon/early evening. Still during temperature inversion conditions with fog, the UHI can affect the magnitude of the temperature inversion by reducing it.

1. Introduction

Fog is a phenomenon that occurs in the atmospheric boundary layer (ABL) and, by definition, consists of suspended water droplets and/or ice crystals in the vicinity of Earth's surface, which leads to reduced horizontal visibility below 1 km (World Meteorological Organization (WMO), 1966). If the horizontal visibility (h) is reduced from 1 to 5 km (in aviation meteorology, International Civil Aviation Organization (ICAO), 2010) or 10 km (WMO, 1966), mist forms instead of fog. As opposed to the fog definition, dense (or heavy) fog is not clearly defined; however, the term dense fog is often used when h is < 200 m (Van Oldenborgh et al., 2010). Water droplets and ice crystals, typically 5–50 μm in diameter, are the result of supersaturation due to cooling, the increase in humidity and/or the mixing of different surface air temperatures (Gultepe et al., 2007). Because of these characteristics, fog has a great influence on all modes of transport (i.e., sea, air and roads) and belongs to the list of hazards. Therefore, fog needs to be successfully detected and predicted because economic losses are sporadically comparable to those after a tornado event (Gultepe et al., 2007).

Since fog develops within the ABL, its initiation and lifetime are strongly influenced by the canopy layer, vegetation, land surfaces (particularly urban surfaces) and soil characteristics. The impact of urban areas can be direct and indirect. Direct impacts include surface

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modification (i.e., the net balance of radiation due to changes in albedo, surface roughness, emissivity, and turbulent fluxes of heat and humidity), which forms higher temperatures (i.e., urban heat island (UHI)) and reduced humidity due to the larger proportion of impermeable substrates, which prevent evaporation. Indirect effects are due to changes in the radiative properties of the urban atmosphere, which are caused by spatial and temporal changes in pollutant concentrations. Therefore, fog is less likely to occur in cities, but it can last longer than fog in rural areas (Tiwari et al., 2011). Both the concentration and size of aerosol particles affect urban fog thickness (e.g., Stolaki et al., 2015). High aerosol concentrations lead to denser fog, which persists longer because urban aerosols have structures that can bind more water than rural aerosols (Van Oldenborgh et al., 2010). Recent climate studies using visibility data have shown a reduction in the number of days with fog in Europe during the period 1976–2006 (Vautard et al., 2009). While some authors (LaDochy, 2005; Li et al., 2012) have argued that decreasing global trends in the number of days with fog/mist can be attributed to the direct effect of the UHI, van Oldenborgh et al. (2010) considered that the cause of this decrease in Europe was due to emission reductions. However, the effect of decreasing trends was mainly found for mist (1 km $< h <$ 5 km).

A similar decreasing trend was observed in the peri-Pannonian area of northwestern Croatia, specifically in the greater Zagreb region during the last 40 years (e.g., Brzoja, 2012; Leko, 2014; Zoldoš and Jurković, 2016), which is the main study area here (Fig. 1). The city of Zagreb is situated on the southern slopes of Medvednica Mountain and the banks of Sava River. Medvednica Mountain shows an insular ridge shape that extends approximately 40 km in the NE-SW direction and a width of 10 km, with the highest peak at an altitude of 1035 m above sea level (asl). The city extends over an elliptical area of 641 km^2 and has a longer *E*-W axis (~25 km) and shorter N-S axis (~15 km). Within this area (Fig. 1b), Zagreb-Grič (ZG1; 45.81°N, 15.98°E; 157 m asl) is in the very center of the city, and Zagreb-Maksimir (ZM; 45.83°N, 16.03°E; 128 m asl) is located in the eastern part of the city. The Zagreb Department of Geophysics (ZG2; 45.83°N, 15.99°E; 182 m asl) lies along the slopes of Medvednica in the north-central region. Approximately 20 km from Medvednica to the south is Zagreb airport (ZA; 45.73°N, 16.06°E; 108 m asl), which is on a very flat terrain with rich underground waters that is mostly covered by grass and small forests. East of ZA is the lowland region of Turopolje, with relatively remote Mount Moslavačka Gora (~487 m asl), which is 10 km south of the airport and has a hilly terrain that includes Vukomerić hills (~255 m asl). West of Zagreb is Samobor Mountain (~880 m asl).

In terms of the climate of the Zagreb region, during the cold part of the year, two influences are primarily dominant: cyclonic activity generated mainly by the Mediterranean and anticyclonic activity over Eurasia. Medvednica protects the Zagreb area from the direct intrusion of cold northern outbreaks (which cause bypasses of the NW-NE synoptic flow around the mountain barrier) and modifies the southern flow by slowing down or forcing it to rise (Lisac, 1984). Medvednica also generates its own local winds during undisturbed weather conditions (Lisac, 1984; Prtenjak et al., 2012). The impact of the Sava River is limited to the surrounding area of the river and could potentially contribute to the creation of fog in the city (Makjanić, 1977).

The climatological analysis of the number of days with fog in the area showed that the ZA station had the highest number of foggy days per year (more than double compared with the ZG1 station). At the ZM station, ~ 25% more days with fog were observed than at the ZG1 station (Brzoja, 2012). For the period 1981–2008, the mean number of foggy days per year was ~ 35 days for the ZG1 station, ~ 43 days for the ZM station and ~ 78 days for the ZA station. According to previous climate analyses of the number of days with fog in the Zagreb area (e.g., Leko, 2014), the maximum occurrence of foggy days was achieved in the sixties, after which it was in a constant decline. Although observed at all abovementioned stations, this decrease is more evident at the urban/suburban stations, ZG1 and ZM (Brzoja, 2012; Zoldoš and Jurković, 2016). There are two reasons why the city stations could be important regarding fog occurrence. The first is the gasification in Zagreb, which has increased due to the use of natural gas (especially since the 90s) and consequently caused an annual decrease in the concentration of total pollution (suspended particulate matter (PM), smoke and SO_2 (Leko, 2014)). The second reason is the impact of UHIs in Zagreb, which has been noted in a few studies (e.g., Perčec Tadić, 2010; Ogrin, 2015). Although UHIs vary seasonally and during the day on average, the city is warmer than its surroundings by at least 1 °C, which also extends the vegetation cycle by approximately 3 weeks (Makjanić, 1977). These are all parameters that can have an impact on fog occurrence in Zagreb.

The airport is located in a rural/suburban environment. At the ZA station, foggy days (e.g., Brzoja, 2012) and fog events (Zoldoš and Jurković, 2016) have maximum occurrences during fog season (September–February; 85% of all fog events); without the observed decreasing trend in the number of foggy days in winter (Brzoja, 2012). Fog at ZA (Zoldoš and Jurković, 2016) is predominantly of the radiation type (in 71% of recorded cases), which forms under calm conditions, lasts up to 12 h (in ~ 78% of all events) and maintains a minimum visibility between 50 and 200 m (~ 71% of the total fog events). If wind exists, then the wind direction is from the SW (more often) and NNE (less often). Furthermore, the seasonal and diurnal frequency distributions of the onset and dissipation of fog events at the airport revealed

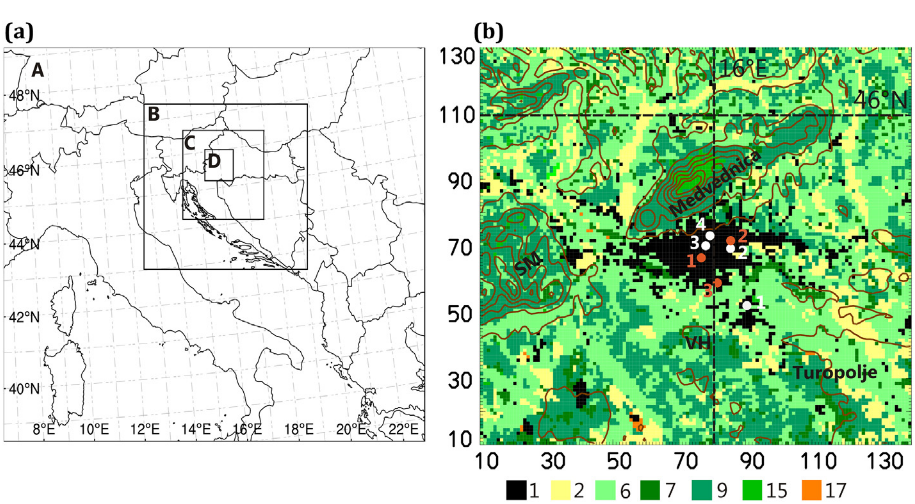

Fig. 1. (a) Four nested model domains (A-D) with a horizontal resolution of 13.5 km (A), 4.5 km (B), 1.5 km (C), 0.5 km (D). (b) The topography (every 100 m) and land cover in the smallest domain (D represents the greater Zagreb area) and the meteorological measuring stations (white): Zagreb airport, ZA (1); Zagreb-Maksimir, ZM (2); Zagreb-Grič, ZG1 (3); Zagreb-Department of Geophysics, ZG2 (4). Air-quality stations (red) from the state network: Zagreb_1 (AQ1-traffic station at the city center), Zagreb_2 (AQ2-suburban area east of Zagreb), and Zagreb_3 (AQ3-suburban area at south of Zagreb). The abbreviations represents the specifications of the topography within the domain (SM = Samobor Mountain and VH = Vukomerić hills). The legend in (b) denotes the land cover type in WRF-ARW model to the following description; 1 = urban and build up land; 2 = dryland cropland and pasture; 6 = cropland woodland mosaic; 7 = grassland; 9 = mixed shrubland grassland; 15 = mixed forest, 17 = herbaceous wetland. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)